PAPER

Isosceles-Trapezoidal-Distribution Edge Tapered Array Antenna with Unequal Element Spacing for Solar Power Satellite

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SUMMARY The Earth will require sustainable electricity sources equivalent to 3 to 5 times the commercial power presently produced by 2050. Solar Power Satellite (SPS) is one option for meeting the huge future energy demand. SPS can send enormous amounts of power to the Earth as the form of microwave (MW). A highly efficient microwave power transmission (MPT) system is needed for SPS. A critical goal of SPS is to maintain highest Beam Efficiency (BE) because the microwaves from SPS will be converted to utility power unlike the MW from communication satellites. Another critical goal of SPS is to maintain Side Lobe Levels (SLL) as small as possible to reduce interference to other communication systems. One way to decrease SLL and increase BE is the edge tapering of a phased array antenna. However, tapering the excitation requires a technically complicated system. Another way of achieving minimum SLL is with randomly spaced element position but it does not guarantee higher BE and the determination of random element position is also a difficult task. Isosceles Trapezoidal Distribution (ITD) edge tapered antenna was studied for SPS as an optimization between full edge tapering and uniform amplitude distribution. The highest Beam Collection Efficiency (BCE) and lowest SLL (except maximum SLL) are possible to achieve in ITD edge tapering and ITD edge tapered antenna is technically better. The performance of ITD is further improved from the perspective of both Maximum Side Lobe Level (MSLL) and BE by using unequal spacing of the antenna elements. A remarkable reduction in MSLL is achieved with ITD edge tapering with Unequal element spacing (ITDU). BE was also highest in ITDU. Determination of unequal element position for ITDU is very easy. ITDU is a newer concept that is experimented for the first time. The merits of ITDU over ITD and Gaussian edge tapering are discussed.

key words: SPS, microwave power transmission, phased array, unequally spaced array, antenna tapering

1. Introduction

The demand for SPS in the 21st Century is discussed in details in [1]. The prosperity of human being on Earth by 2050 will require sustainable electricity sources equivalent to 3 to 5 times the commercial power presently produced [2]. Global warming is another key problem in the 21st century. Electricity generated from any renewable energy source, such as hydro, wind, biomass, geothermal and solar, is considered "green" because of the negligible impact on greenhouse gas emissions [3]. One source of clean, safe, low-cost commercial electricity from solar power via the moon is described in [2]. The first idea of Solar Power Satellite (SPS) was conceived by Peter Glaser in 1968 [4]. The idea of

Glaser paved the way for DOE/NASA study of microwave (MW) power transmission from satellite. Solar panels of the SPS would be placed in geostationary orbit (GEO) at a distance 36000 km from the Earth's surface. Beam Efficiency (BE)/Beam Collection Efficiency (BCE) and Maximum Side Lobe Level (MSLL) are the indices for the evaluation of the MW beam. BE is the ratio of energy flow within the main beam to the whole transmitted power. Similarly BCE of the Microwave Power Transmission (MPT) systems is the ratio of energy flow that is intercepted by the rectenna to the whole transmitted power. The word "rectenna" is derived from the words "rectifying antenna." Rectenna is the receiving antenna for the MW power from the SPS. The received MW power on the rectenna will be converted to the utility power. BE for two dimensional beam pattern quantifies the solid angle extent of the main beam relative to that of the entire pattern and can be expressed as [5]:

$$BE_{2D} = \iint_{main\_beam} |P(\theta,\phi)|^2 \, d\Omega \bigg/ \iint_{4\pi} |P(\theta,\phi)|^2 \, d\Omega \quad (1)$$

Here, $P(\theta,\phi)$ is the radiated electric field.
BE for one dimensional case can be expressed as:

$$BE_{1D} = \int_{\theta_m} |P(\theta)|^2 \, d\theta \bigg/ \int_{\theta_w} |P(\theta)|^2 \, d\theta \quad (2)$$

θ_m is the angle sector due to one dimensional main beam and θ_w is the angle sector of ±90°.
$P(\theta)$ is the one dimensional radiated electric field.

Equations for the calculation procedure of BCE are described in [6] those are very similar to Eqs. (1) and (2). The numerator of the above equations is to be replaced by the size of rectenna during the calculation of BCE.

Suppression of Grating Lobes (GL) and Side Lobe Levels (SLL) is necessary for higher BCE and to avoid interference to other communication systems. If GL appear and SLL increase, the transmitted power will be absorbed into these lobes which will cause reduction of BE/BCE and interference will also increase. A phased array antenna has been proposed in SPS system to maintain higher BCE. If all antennas are uniformly excited then the main beam will carry only a part of the total energy due to higher SLL. The targeted BCE for SPS is 90% to reduce the cost. It has been seen that it is possible to increase BCE and reduce SLL if edge tapering system can be adopted in MPT antennas.

An optimized circularly symmetrical amplitude distribution for MPT is described in [7] to achieve maximum

transmission efficiency with constraint on the power levels outside the receiving aperture. A 10 dB Gaussian taper has been discussed in [8]–[10] and has been proposed in the NASA/DOE model [11] and JAXA model. Other methods of maximizing the electromagnetic power with some constraints have been discussed in [12], [13]. A conceptual study of amplitude tapering effect for low SLL has been presented in [14]. Taylor aperture distribution pattern has been presented in [15] for array design. A new approach of designing Chebyshev array has been presented in [16] where some new equations have been derived to estimate the excitation currents. Though the best form of amplitude distribution is known to be the Gaussian at the same time it has the demerits of poor use of radiating antenna surface [17] and the references there in]. One possible solution is described in [18] by introducing discontinuous antenna radiators distribution. A comparison between Taylor amplitude tapered array and statistically thinned array is shown in [19]. The main beam and the near in SLL behavior of the two patterns were similar but the SLL of the statistically designed thinned array was higher than that of the Taylor design over a large part of the angular region [Fig. 3 of 19]. Though this difference is not that important for many other practical array applications but this will cause a reduction of BCE in MPT application. Therefore MPT designers must be concerned with the BE/BCE when they design phased array with thinned array, or random array concepts. Moreover the manufacturability of thinned/random array needs to be accounted for during design cycle. It is mentioned in [20] according to the reference [21] that almost 100% efficiency can be achieved by edge tapering which is essentially Gaussian distribution [Fig. 2, Fig. 3 of reference 20 and Fig. 5 of reference 21]. Optimized Gaussian tapering can be used in MPT to increase the energy transmission efficiency. But the effectiveness of MPT also depends on the uniformity of amplitude distribution along the surface, i.e. maximum utilization of antenna surface. It has been discussed in [6] that edge tapering for SPS like optimized Gaussian, Chebyshev, and Taylor distribution has some complexity of different power output levels at different antennas and problem of heat radiation and an optimization was proposed between optimized Gaussian distribution and uniform amplitude distribution. It was shown [6] that the highest BCE and lowest SLL (except MSLL with lower number of antennas to be tapered) can be achieved with ITD. ITD edge tapering is comparatively a new idea of phased array power distribution based on Isosceles Trapezoid. A most technological and effective method is needed for MPT. The amplitude distribution in ITD is almost uniform which is technically easy to build and better use of antenna surface can be achieved by ITD. Even in optimized Gaussian distribution the use of antenna surface is still poor. The performance of ITD is further improved from the perspective of both Maximum Side Lobe Level (MSLL) and BE/BCE by using combined equal and unequal spacing of the antenna elements.

The amplitude distribution of ITDU is same as that of ITD and is also technically better than that of Gaussian distribution. The unequal element spacing is derived from the ITD concept and by using the sinc function. No grating lobe in the observation range of $\pm 90°$ is formed due to unequal spacing with ITD. The determination of unequal element spacing for ITDU is much easier than that of thinned array or random array and it will be technically easier to be built.

An experimental result on ITDU is discussed. The mutual coupling effect is neglected in this paper. The validity of ITDU by using element spacing range of 0.6λ–0.8λ and beam steering angle of $10°$ with the array broadside is discussed. For real SPS application the beam steering angle will be within $\pm 5°$ with the array broadside and it is possible to use the antenna spacing between 0.58–0.8λ for SPS system and it would be possible to push the mutual coupling to lower levels. The authors' group is presently working on the effect of mutual coupling. It is negligible under such spacings. The performance of ITDU for two dimensional (2D) arrays is also discussed.

2. Isosceles Trapezoidal Distribution Tapering

The concept of ITD for one dimensional (1D) array is shown in Fig. 1. In this method amplitude of only a few edge transmitting antennas/units are tapered. Amplitudes of remaining most antennas/units are uniform. In recent SPS design, a concept of "unit" is adopted. Each unit consists of several phased array antenna elements. For example 25 elements or 10 elements can be considered as a "unit."
Array Factor (AF) with ITD is:

$$AF = \sum_{n=1}^{N_t} A_{tn} e^{jn\psi_1} + \sum_{m=1}^{N} e^{j(m+N_t)\psi} + \sum_{n=1}^{N_t} A_{tn} e^{j(n+N_t+N)\psi_2} \quad (3)$$

where, N = Number of SPS units with uniform amplitudes,
N_t = Number of units tapered from each side,

$\psi = \beta D_u (\sin\theta - \sin\theta_0)$.
$\psi_1 = -\beta D_u (\sin\theta - \sin\theta_0)$.
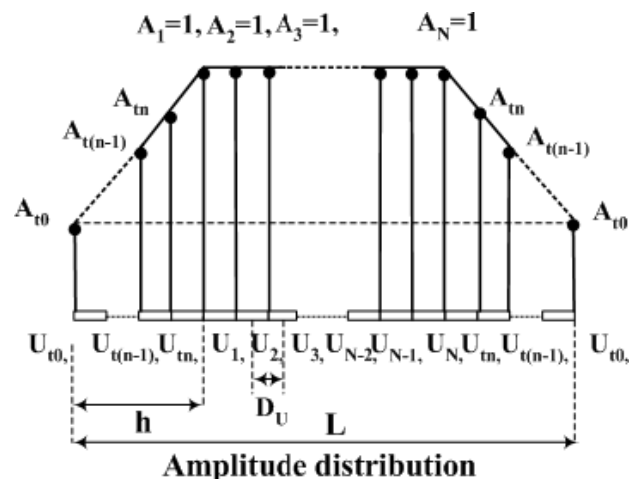$\psi_2 = [(N-1)D_u + nD_u](\sin\theta - \sin\theta_0)\beta$.

Fig. 1 ITD type edge tapering for SPS transmitting antennas.

D_u = inter-unit spacing (m).

N_T = Total number of antenna units = $N + 2N_t$.

$\beta = 2\pi/\lambda$ = phase constant.

The amplitude distribution of the ITD tapering is:

$$A_{tn} = (1 - A_{t0})n/N_t + A_{t0} \qquad (4)$$

A_{t0} is the amplitude of each of the end units.

θ_0 = Direction of beam maximum along the broad side.

$$n = 0, 1, 2 \ldots N_t, \quad 0 \le A_{tn} \le 1$$

In Fig. 1,

h = Length of the antennas tapered from each side.

L= Total length of the array

$A_1 = A_2 = A_3 = \ldots = A_N = 1$ (normalized maximum power).

$m = 1, 2, 3 \ldots N$.

3. Determination of Unequal Element Spacing for ITDU

The Isosceles Trapezoidal Distribution in Sect. 2 is explained for the power distribution of antenna units. The same ITD expression (Eq. (4)) can be used when antenna elements are considered instead of antenna "units" and can be used for the determination of unequal spacing of phased array antenna elements. Let us consider the isosceles trapezoidal amplitude distribution is $A(x)$ which is similar to Eq. (4). Here $A(x)$ is only the amplitude distribution of an isosceles trapezoid and not the power distribution of the antennas as is considered in Sect. 2. The variable x is the position of antenna elements (for example positions 1, 2, 3, etc in Fig. 2). Next we want to determine a factor for the determination of unequal element spacing for ITDU that will be multiplied by the equal element spacing. Let us call this multiplying factor $M(x)$. If the equal element spacing for

Fig. 2 ITD type edge tapering for 101 phased antenna elements and multiplying factor for unequal spacing of ITDU edge tapered antenna elements. In this figure 30 elements from each side were tapered and 40 elements from each side were of unequal spacing.

ITD is d then the unequal element spacing for ITDU will be d × $M(x)$. And now if we take the sinc function of $A(x)$, the multiplying factor $M(x)$ for the determination of element spacing is to be expressed as Eq. (5):

$$M(x) = \text{Sinc}[A(x)]/\min\langle \text{Sinc}[A(x)]\rangle$$
$$= \text{Sinc}[A(x)]/0.8415 \qquad (5)$$

If the total number of elements is (2P + 1) then the range of x is from 1 to 2P. Though several other distributions (like Gaussian, cosine, etc.) were tried to determine the unequal spacing it was found that the sinc function of $A(x)$ best fits for the determination of unequal element spacing in order to reduce MSLL and maintain highest BE/BCE. One example of ITD edge tapering, ITD for element spacing, multiplying factor $M(x)$ and element spacing for ITDU of 101 phased array antenna elements is shown in Fig. 2. The steps for the determination of edge tapering and unequal element spacing for ITDU of 1D array are described here:

Step 1: Select the number of antennas to be tapered for unequal power distributions from each side of the phased array antenna according to Curve 1 of Fig. 2. For example 30 elements are selected from both sides for ITDU edge tapering in this figure. Remaining middle 41 elements will of uniform power distribution.

Step 2: Select another Isosceles Trapezoid for the determination of unequal element spacing of ITDU. Curve 2 [$A(x)$] is selected for the determination of unequal element spacing in Fig. 2. In this example 40 elements from each side are selected those will be of unequal spacing. Remaining middle 21 elements will of equal spacing.

Step 3: Take the sinc function of curve 2 [$A(x)$] to obtain curve 3 [$M(x)$] by using Eq. (5).

Step 4: Determine the value of equal element spacing. It was discussed before in Sect. 1 that it is possible to use the antenna spacing between 0.58–0.8λ for SPS system. The value of equal element spacing should be chosen in such a way that the value of maximum element spacing remains within this range. The value of equal element spacing is taken 0.68λ in this example.

Step 5: Multiply the value of equal element spacing with $M(x)$ to obtain the values of unequal element spacing (curve 4). The values of curve 4 are a combination of equal and unequal element spacing. The middle 21 elements of curve 4 are of equal element spacing of 0.68λ and the remaining elements are of unequal spacing and the values are symmetric. This is one merit of ITDU over random array/thinned array. Because the values of element spacing in ITDU can be calculated easily from Eq. (5), but the element spacing in random/thinned array is difficult to determine. The fabrication process of ITDU will also be easier than that of random/thinned array. The purpose of taking the difference in number of elements to be tapered and number of elements of unequal spacing is the improvement of beam forming and will be discussed in details later in Sect. 4.

In the following sections the BE is calculated instead of BCE. If BE is highest then BCE will also be highest when
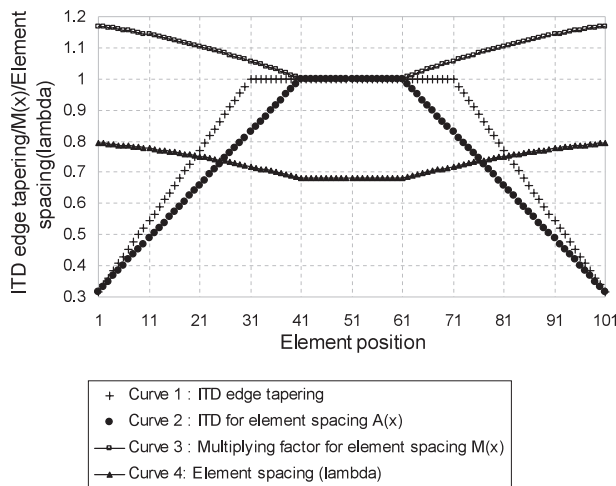
the size of the rectenna is equal to or greater than the size of the main beam on rectenna. It is also possible to consider antenna "unit" in the following sections. But the number of elements for ITDU and that for other distributions are different. That's why a comparative study is done by considering only elements. The reason of taking the different elements is to keep the same phased array antenna length for ITDU and for other kinds of distributions. Phased array antenna length of 109 elements of equal element spacing of 0.68λ (for uniform, Gaussian and ITD edge tapering) is same as the phased array antenna length of 101 elements of ITDU of Fig. 2.

4. Comparative Study of Different Amplitude Distribution System for Different Tapering Level and Beam Steering Angle

Radiation patterns, MSLL and BE for different tapering levels, inter-element spacing, beam steering angles and for Uniform, Gaussian, ITD and ITDU power distribution systems were compared and summarized in Table 1. The normalized radiation patterns for case 1 of Table 1 are shown in Fig. 3. Case 1 is for Uniform power distribution (109 elements of spacing 0.68λ), $-10\,$dB Gaussian edge tapering (109 elements of spacing 0.68λ), $-10\,$dB ITD (109 elements of spacing 0.68λ), $-10\,$dB ITDU ((101 elements of spacing

ranging from 0.68λ to 0.795λ) and 0° beam steering angle from array broad side. Similarly case 5 of Table 1 is same as case 1 but the beam steering angle is 10° in this case and the element spacing range is from 0.6λ to 0.7λ for ITDU. The uniform element spacing for all other distributions in case 5 is 0.6λ. The reason of reducing the element spacing range for 10° beam steering angle is to avoid higher SLL in ITDU. This element spacing range is still acceptable for SPS from the view point of maximum beam steering angle, grating lobes and mutual coupling effect.

The power at the center of the transmitter can be made lower in ITD/ITDU than that of Gaussian distribution which is another merit of ITD/ITDU over Gaussian power distribution. One example of power distributions of total 109 watts power for uniform, $-10\,$dB ITD, -10 ITDU and $-10\,$dB Gaussian edge tapering (case 1) is shown in Fig. 4. The number of antennas in Uniform, Gaussian and ITD edge tapering is 109 and that in ITDU is 101. The power distribution at the center of the transmitter is the highest in Gaussian distribution which is a demerit because of thermal problem and other technical problems. Element spacing for ITD, Gaussian and uniform distribution was equal. The power distribution at the center of ITDU is higher than that of ITD edge tapering, because the number of antennas is less in ITDU than that in ITD. The power distribution in ITDU can be made identical to that of ITD by considering 109 an-

Table 1 BE and MSLL for different edge tapering systems with different antenna elements, tapering levels, beam steering angles and inter-element spacing.

Types of tapering	Cases	No. of elements	Tapering levels (dB)	Beam steering angles (deg)	No. of Elements tapered	Elements of unequal spacing	Element spacing ranges (lambda)	BE (%)	MSLL (dB)
Uniform	1	109	0	0	0	0	0.68	89.54	-13
	5			10	0		0.6	89.8	-13
Gaussian	1	109	-10	0	all	0	0.68	98.33	-22.46
	2	53909	-10					99.96	-22.5
	5	109	-10	10			0.60	98.6	-22
ITD	1	109	-10	0	33	0	0.68	98.30	-18.7
	3		-20					98.76	-18.8
	2	53909	-10		16172			98.31	-18
	4		-20					98.84	-18.8
	5	109		10	33		0.60	98.2	-19
ITDU	1	101	-10	0	30	40	0.68~0.795	98.97	-26
	3		-20			37	0.68~0807	99.69	-32
	2	50001	-10		15000	20000	0.68~0.795	99.999	-26
	4		-20			18500	0.68~0807	99.84	-32
	5	101	-10	10	30	40	0.6~0.7	99.06	-26
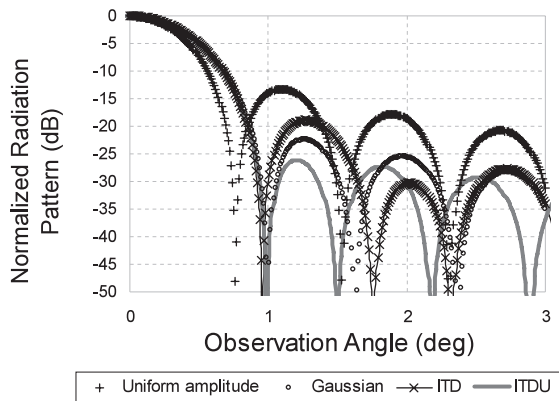
Fig. 3 Normalized radiation patterns for phased array antenna of uniform amplitude, $-10\,\mathrm{dB}$ Gaussian tapering, $-10\,\mathrm{dB}$ ITD and $-10\,\mathrm{dB}$ ITDU. 33 elements from each side were tapered in ITD. 30 elements from each side were tapered in ITDU and 40 elements from each side were of unequal spacing in ITDU.
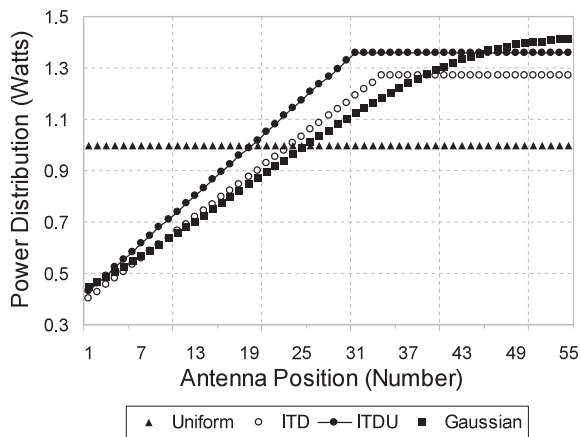

Fig. 4 Uniform amplitude distribution, $-10\,\mathrm{dB}$ ITD (33 elements tapered), $-10\,\mathrm{dB}$ ITDU (30 elements tapered and 40 elements are of unequal spacing) and $-10\,\mathrm{dB}$ Gaussian power distribution for total 109 watts power in each case (The number of elements in ITDU is 101 and the number of elements in each of the other cases is 109). Power distributions for half of the arrays are shown in the figure. Power distributions for rest half of the arrays are symmetrical.

tennas in ITDU or by decreasing the number of antennas tapered from both side. But if the number of antennas tapered is decreased then there will be a little increase of MSLL. Radiation pattern for $10°$ beam steering angle of ITDU of case 5 is shown in Fig. 5. The MSLL and BE were also measured for 101 phased array antennas of ITDU ($-10\,\mathrm{dB}$) by varying the number of elements tapered and number of elements of unequal spacing from both sides and is summarized in Table 2. It was found that the MSLL was lowest ($-26\,\mathrm{dB}$) when 30 elements were tapered and 40 elements were of unequal spacing from both sides. BE was also the highest (98.97%) in this case. Though the MSLL was even lower ($-24.5\,\mathrm{dB}$) in ITDU than that of Gaussian distribution ($-23\,\mathrm{dB}$) when the number of elements tapered was same as the number of elements of unequal spacing in ITDU (30 elements in this case as shown in Table 2). For large number
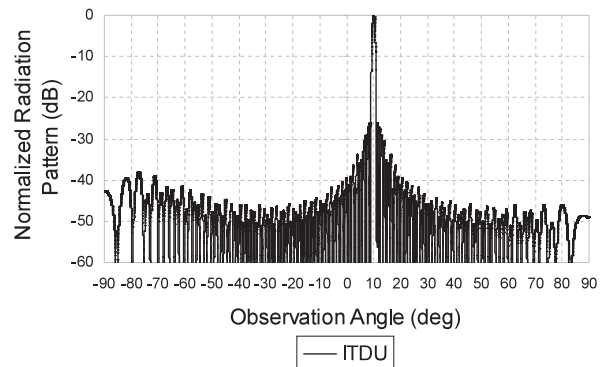

Fig. 5 Normalized radiation pattern for 101 phased array antenna of $-10\,\mathrm{dB}$ ITDU and observation range of $\pm\,90$ deg for 10 degree beam pointing angle. 30 elements from each side were tapered and 40 elements from each side were of unequal spacing.

Table 2 Different values of MSLL and BE for different number of elements tapered and number of unequal element spacing for 101 phased array antennas and $-10\,\mathrm{dB}$ ITDU tapering.

No. of elements tapered from both side	30	30	40	40
No. of elements of unequal spacing from both side	30	40	30	40
MSLL (dB)	-24.5	-26	-23	-22
BE (%)	98.70	98.97	98.22	98.50

of antenna elements (case 2 & 4 of Table 1) and for higher tapering level (case 3 & 4) ITDU also performed better and can be verified from Table 1. The observation range was $\pm0.01°$ for case 2 and case 4. The BE was higher in case 3 ($-20\,\mathrm{dB}$) of ITDU than that of case 1 ($-10\,\mathrm{dB}$) of ITDU. On the other hand BE was higher in case 2 ($-10\,\mathrm{dB}$) of ITDU than that of case 4 ($-20\,\mathrm{dB}$) of ITDU. The reason of the difference of this BE tendency is that the observation and calculation range for BE was $\pm0.01°$ (that has been mentioned before) for case 2 and case 4 instead of observation range of $\pm90°$. The observation range and calculation range for BE for case 1 and case 3 was $\pm90°$.

The BE becomes different for different observation ranges. It was not possible to simulate the radiation patterns for higher number of elements (of case 2 and 4) with higher observation range due to memory problem of the computer.

In case 1-2 ($-10\,\mathrm{dB}$ tapering) and in case 3-4 ($-20\,\mathrm{dB}$ tapering) of ITDU the number of elements of unequal spacing were different (column 7 of Table 1). The main reason of this difference is that when 40 elements were chosen from the both side for unequal spacing of $-10\,\mathrm{dB}$ ITDU (case 1) the best MSLL and BE performance was achieved that has already been explained and shown in Table 2. But for $-20\,\mathrm{dB}$ ITDU (case 3) the best MSLL performance was attained when 37 elements were chosen for unequal element spacing. The same reason applies for case 2 and case 4 of ITDU.

From Tables 1, 2 and from Figs. 2–5 it can be seen that the ITDU which is a new concept shows better MSLL/BE performance than any other kinds of distributions, even for

higher beam steering angle and higher level of tapering. The determination of unequal spacing for ITDU which is within the range of real SPS application is also easier unlike the determination of element spacing for random/thinned array. For example the MSLL for −10 dB ITDU and 10° beam steering angle is −26 dB (case 5) and BE for the same situation is 99.06% and those for Gaussian and ITD of the same case are −22 dB/98.6% and −19 dB/98.2% respectively.

5. Experiment with ITDU

A laboratory experiment on ITDU was conducted by using the SPORTS (Solar POwer Radio Transmission System) 5.8 GHz "beam forming subsystem" in the Microwave Energy Transmission LABoratory of the Kyoto University. A detailed discussion on SPORTS 5.8 is done in [6]. 11 phased array antenna elements with unequal spacing, as shown in Fig. 6, were used during the experiment.

Simulated and measured amplitude distribution of the antenna elements as well as simulated inter-element spacing and inter-element spacing during the experiment are shown respectively in Table 3 and Table 4. Figure 7 shows the radiation patterns for ITDU and for three different situations of simulation, measurement and simulation with some real errors and the simulated radiation pattern for ITD. From Table 3 and Table 4 it can be seen that there were some dissimilarities between simulation and measurement of amplitude distributions and element spacing. Moreover the attenuators used for the experiment had some phase errors. The assumed amplitude distributions and phase errors those were used during the simulated radiation pattern with errors are shown respectively in rows 3 and 4 of Table 3. There is a difference between measured and simulated (with errors) radiation patterns after the experiment because it was not possible to find out the exact errors during experiments. There might have been some errors due to reflection from other parts. The purpose of showing the simulated radiation pattern (with errors) is that when these kinds of errors exist in real situation the radiation pattern changes abruptly with increased SLL which is not desirable. The simulated MSLL was about −28 dB (2nd SLL in this case) within the observation range of ±30° and measured MSLL was about −25 dB (less than those of −10 dB ITD and −10 dB Gaussian edge tapering). The MSLL for −10 dB Gaussian edge tapering is about −23 dB and that of −10 dB ITD is about −20 dB (Fig. 7). The simulated first SLL (about −31 dB) also agree well with measured first SLL (about −29 dB) in ITDU and can be seen from Fig. 7. Therefore from this experimental and simulated data it can be confirmed that ITDU is the best when it is compared with ITD and Gaussian edge tapering.

6. ITDU with 2D Array

The radiation patterns for −10 dB and −20 dB ITDU with 101 × 101 2D phased array antennas were studied. The radiation patterns for −10 dB ITD and −10 dB Gaussian distribution (109 × 109 elements) were also studied. Figure 8
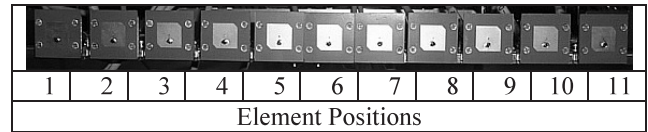

1	2	3	4	5	6	7	8	9	10	11
				Element Positions						

Fig. 6 Phased array antenna elements of SPORTS 5.8 with unequal element spacing for experimentation on ITDU.

Table 3 Simulated and measured amplitude distributions and simulated phase errors of 11 phased array antenna elements and for −10 dB ITDU.

Element Number ⇨	1	2	3	4	5	6	7	8	9	10	11
Simulated Amplitude Distribution	-10	-5.90	-2.25	0	0	0	0	0	-2.25	-5.90	-10
Measured Amplitude Distribution	-10.70	-6.42	-3.65	0	0	0	0	0	-3.62	-6.70	-10.54
Phase Error Considered during the Simulation of Error (deg)	26	8	12	0	0	0	0	0	5	7	22

Table 4 Simulated and experimental inter-element spacing (cm) of 11 phased array antenna elements and for −10 dB ITDU.

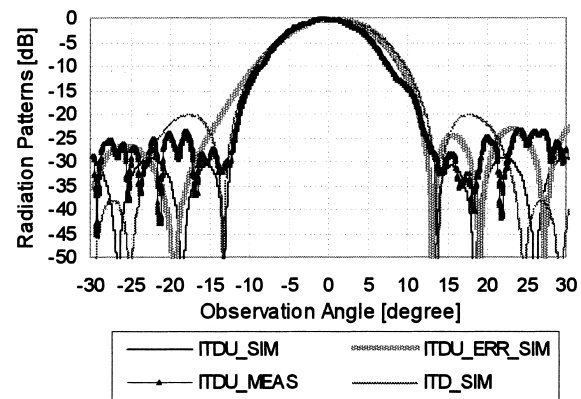| Element Numbers ⇨	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11
Simulated inter-element spacing (cm)	3.63	3.54	3.43	3.3	3.05	3.05	33	3.43	3.54	3.63
Experimental inter-element spacing (cm)	3.6	3.5	3.4	3.3	3.0	3.0	3.3	3.4	3.5	3.6

Fig. 7 Simulated, measured and simulated (with error) radiation patterns of ITDU and simulated radiation pattern for ITD with 11 phased array antenna elements.

shows the projected radiation patterns of −10 dB ITDU in XY, YZ and ZX planes. The MSLL for ITDU, Gaussian and ITD were −26 dB, −22 dB and −18.75 dB respectively and BE were 99.82%, 99.34% and 98.82% respectively for observation angle of ±30°. It can be concluded from this simulation and the 1D simulation case of the same situation that
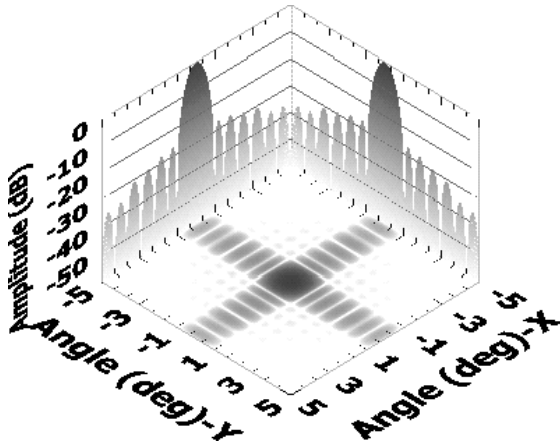
Fig. 8 Three dimensional projected beam pattern for −10 dB ITDU of two dimensional arrays in the XY, XZ and YZ planes. Projected pattern in the XY plane is the contour plot of the radiation pattern.

Table 5 Comparative study of different kinds of amplitude distribution system for two dimensional arrays.

Type of Tapering	Tapering Level (dB)	MSLL(dB)	BE (%)
ITDU	-10	-26	99.82
Gaussian	-10	-22	99.34
ITD	-10	-18.75	98.82

the BE for ITDU would be the highest with −26 dB MSLL. 30 elements were tapered in ITDU from both sides of the X and Y dimensions of the array and 40 elements from both sides of the X and Y dimensions were of unequal spacing ranging from 0.68λ to 0.795λ. 33 elements from both sides of X and Y dimensions were tapered in ITD. The simulation results are summarized in Table 5. Well performance was also achieved in −20 dB ITDU tapering. It is important to mention here that the same rectenna width was considered for different edge tapering system in [6] during the calculation of BCE. But the main beam width is considered, which may be different for different edge tapering/amplitude distribution system, during the calculation of BE.

7. Conclusions

Different kinds of amplitude distributions for SPS phased array transmitting antennas are compared and discussed. Edge tapering is needed for higher Beam Efficiency (BE) in Microwave Power Transmission (MPT) but it has thermal and technical complexities. Statistically thinned array antenna can reduce some SLL but there is a possibility of increasing other SLL which can cause reduced BE. Moreover it is difficult to determine the element spacing of thinned/random array. Therefore an optimization is needed between full edge tapering and uniform amplitude distribution. An optimization between full edge tapering and uniform amplitude distribution with equal element spacing is sought by incorporating Isosceles Trapezoidal Distribution (ITD) edge tapering and was discussed in [6]. With ITD it is possible to maintain higher BCE but higher number of antennas is

needed to achieve lower MSLL. Though ITD is still better than Gaussian distribution when BCE, power distribution and other SLL are compared.

Another optimization between ITD and ITD with Unequal spacing (ITDU) to achieve lower MSLL and higher BE is presented in this paper. It is possible to maintain highest BE and lowest MSLL by incorporating ITDU edge tapering of phased array antenna in MPT system. ITDU is a new concept and it was shown in Tables 1, 2 and Figs. 2–5 that the MSLL/BE performance of ITDU is better than those of ITD and Gaussian distributions, even for higher beam steering angle and higher tapering level. The element spacing for ITDU is very easy to determine and within the range of real SPS application. But the determination of element spacing for thinned/random array is difficult. In case 5 of Table 1 it is shown that the MSLL for −10 dB ITDU edge tapering and for 10° beam steering angle is −26 dB and BE for the same situation is 99.06%. MSLL for ITD and Gaussian edge tapering of case 5 are −19 dB and −22 dB respectively. BE for ITD and Gaussian are 98.2% and 98.6% respectively for case 5. The performance of ITDU edge tapering for two dimensional case is also same as that of one dimensional case. The power distribution at the centre of the phased array antenna for ITDU case can be made lower than that of Gaussian distribution which is another benefit of ITDU over Gaussian amplitude distribution. Maximum power will be transmitted through the main beam and less power will be in the SLL in case of ITDU even when the same power will be sent for the Gaussian, ITD and ITDU edge tapering. Therefore the exposure level to humans and all other living animals/things outside the rectenna area is less due to ITDU when it is compared to that of Gaussian distribution or ITD. An experimental result of ITDU is also presented which confirmed that better performance of ITDU over ITD and Gaussian edge tapering is possible. Therefore the best form of power distribution for SPS phased array transmitting antenna can be considered to be the ITDU. Further study/experiment on ITDU is needed to test the applicability of the distribution in SPS context.

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